

Gallium Nitride Direct Energy Conversion Betavoltaic Modeling and Optimization

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Abstract: *This paper analyzes the use of a wide-bandgap betavoltaic towards use as a long lasting low power battery for various applications. The paper establishes a model for gallium nitride betavoltaics through use of experimentation and software tools. Software tools include Silvaco ATLAS and MCNPX, a simulation model is formed and analyzed to identify the parameters that create the most impact on optimization. Optimization can only occur through a verified model. The depletion region provides the most discernible effect towards device efficiency. Design approaches that best match the beta range to the limits of gallium nitride device characteristics are discussed.*

Keywords: betavoltaic; gallium nitride betavoltaic; wide-bandgap betavoltaic; beta-photovoltaic; betaphotovoltaic; tritium; low power high energy battery; betavoltaic battery; Silvaco ATLAS; semiconductor device simulation; MCNPX

Introduction

A growing problem in power electronics is high energy density, long lasting power sources where the capability to provide a stable power source or high-maintenance power sources is unavailable or too costly to use. This problem has led to the research behind Gallium Nitride (GaN) betavoltaic systems due to their ability to convert high energy density sources into electricity.

The Internet of Things (IoT) has led to the development of miniaturized systems and sensors, adding the capability to put autonomous sensors on a grander scale. Autonomous sensors could be used by being placed in situations where replacement of the power source is difficult such as inside concrete pillars of bridges to measure the stress. However, the cost-effectiveness of autonomous systems and sensors in remote locations is limited directly by the power source. Autonomous systems such as space satellites require power sources that have strict size, weight, and power (SWaP) limitations, which require high energy density battery systems.

Radioisotopes are the most energy dense materials that can be converted into electrical energy. Pure beta radioisotopes can be used towards making a long-lasting battery. However, the process to convert the energy provided by a pure beta radioisotope requires additional components, specifically through either converting radiation to optical energy, which is then converted to electrical energy, or

through converting radiation to electrical energy directly. The first process, indirect energy conversion, requires a light-emitting material such as a phosphor to convert the radiation into photons, which then requires a photovoltaic cell to convert the photons into electrical energy.

This conversion process, called beta-photovoltaics, has a system efficiency that is dependent on both the conversion efficiency of the phosphor and the photovoltaic cell. Direct energy conversion uses a semiconductor that can convert beta radiation directly into electrical energy, called a betavoltaic. Each energy conversion method has different challenges to overcome to improve the system efficiency. These energy conversion methods that are dependent on beta sources have made forays into the commercial realm, providing very low power for 20+ years [1].

Beta-photovoltaics have been used to fabricate long lasting power sources based on tritium (³H) [2]. Research has shown that scaling this technology could fabricate a 100 μ W battery, effectively providing 9 J per day for autonomous systems. However, the volume for beta-photovoltaics is larger due to the need for phosphors to generate photons. The effective system efficiency is also limited due to relying on two conversion efficiencies. Beta-photovoltaics presents difficulties due to the multiple processes that need optimization to improve overall efficiency and size. Betavoltaics only requires the optimization of the semiconductor.

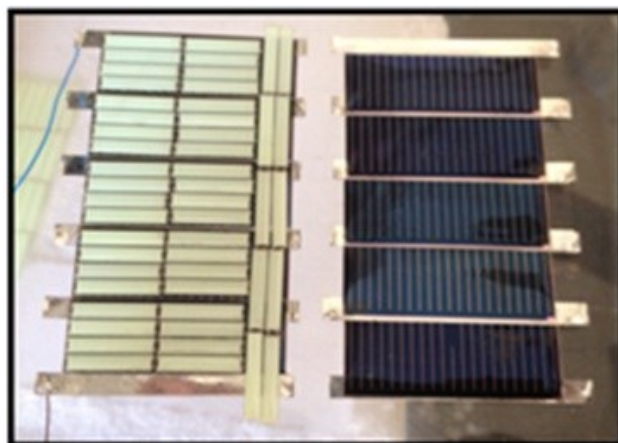


Figure 1. Example of betaphotovoltaic materials, phosphor and tritium on the left, photovoltaics on the right. [2]

GaN Betavoltaic Model

GaN Betavoltaic Advantages: The betavoltaic systems previously developed relies on betavoltaic materials with a relatively small bandgap, such as Silicon [3], that are not as efficient in converting beta radiation into electrical energy. Klein shows that the efficiency of the betavoltaic cell increases as the bandgap of the semiconductor material increases [4]. SiC and GaN specifically are shown to occur near an inflection point of the efficiency vs bandgap curve. As GaN semiconductor fabrication has matured, the capability to use GaN as a betavoltaic has become viable. GaN has many attractive properties such having a large bandgap, being radiation hard to the energies that pure beta sources emit [5], and being a more dense material, which allows for thin devices to absorb radiation.

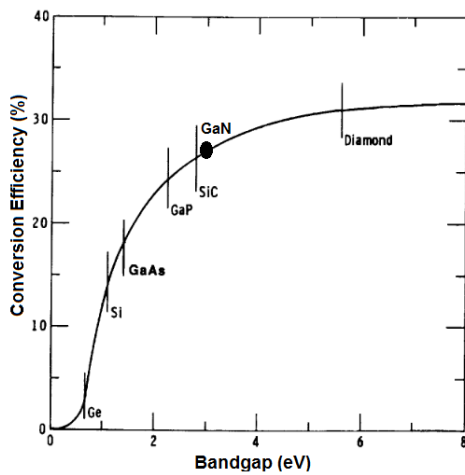


Figure 2 Efficiency vs. Bandgap curve established by the Klein equation. [6]

Current GaN semiconductor fabrication capabilities impose limitations onto the betavoltaic system. GaN device fabrication, specifically vertical p-n junction and P-i-N device fabrication, currently have material defects and fabrication that need to be considered in the design of a betavoltaic cell system [7]. The defects have led betavoltaic cell design away from p-n designs typically used in photovoltaics to a P-i-N design to maximize radiation energy capture. The current capabilities of GaN betavoltaic cell needs to be understood and optimized to establish effective energy converting systems.

GaN Device Experiment: Creation of a model for simulation and estimation purposes was the first step to optimizing the GaN betavoltaic cell. This is performed in a 2-step process, first by the experimentation performed upon a GaN device and then modelling a GaN device for use in semiconductor modeling software. To simulate the beta spectrum of ^3H , a Kimball Physics EMG-12 electron gun, capable of supplying a monoenergetic electron beam ranging from 0 to 16 keV, was used. Beam current on target is measured using a picoammeter along with a Faraday cup. The target is a GaN

P-u-N diode shown in Fig. 3 grown on a Al_2O_3 substrate by State University of New York Albany using a Veeco D180 MOCVD reactor. GaN dopant values and fabrication process are explained in detail in Khan et al. [8]. The wafer was fabricated at the US Army Research Laboratory, Adelphi, Maryland. For p-type contacts, titanium (Ti) (500 Å)/gold (Au) (1,500 Å) is deposited using electron beam deposition. The mesas are etched in an ULVAC NE-550e high-density plasma etcher. Ti (250 Å)/aluminum (Al) (2,200 Å)/nickel (Ni) (600 Å)/Au (500 Å) was then deposited for n-type contacts using e-beam deposition. Both the p- and n-type contacts are annealed at 500 °C in nitrogen gas ambient.

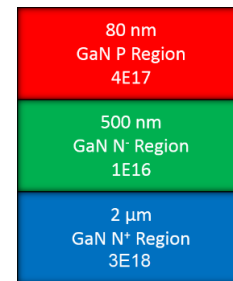


Figure 3 GaN device as fabricated [2]

During electron beam irradiation, the device's current and voltage is measured by a HP 4155B parameter analyzer. Two stainless steel foil apertures ($\varnothing \approx 560 \mu\text{m}$) are placed over the Faraday cup and device to measure beam current density. Electron beam energy is varied from 2.5 keV to 16 keV while the total current through aperture is maintained at approximately 100 pA. The maximum power point (MPP) is calculated for each applied voltage. Power conversion efficiency was calculated using the device output power density over input electron beam power density. Fig. 4 shows the device power efficiency as function of electron energy. The energy conversion efficiency reaches a maximum of 4.5% for 12 keV electron energies.

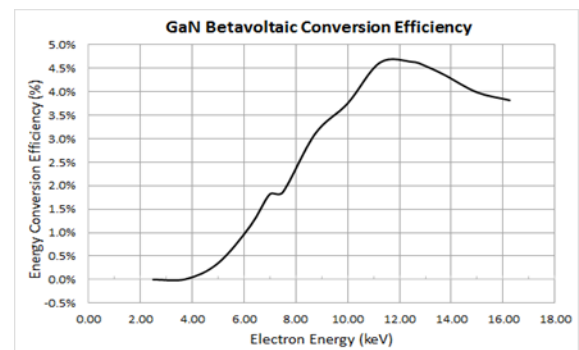


Figure 4 GaN device energy conversion efficiency vs input electron beam energy [2]

GaN Device Software Model: The betavoltaic results are modeled in MCNPX and Silvaco ATLAS in order to understand the device parameters such as material characteristics and radiation energy deposited into the

device. The maximum energy deposited within the first 4 layers came from 12.5-keV electrons. This is consistent with the Silvaco ATLAS device simulation [9]. Thus, the collection of EHPs that contribute to current is dominated by the depletion region collection. The difficulty in measuring the details of reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency, and conductive efficiency makes FF a useful parameter in evaluating performance. Cells with a high FF have a low series resistance and a high shunt resistance. The high shunt resistance is essential for low current devices to be useful, so less of the current produced by the cell is dissipated in internal losses. Fig. 5 shows an example simulation of the dark current of the GaN device.

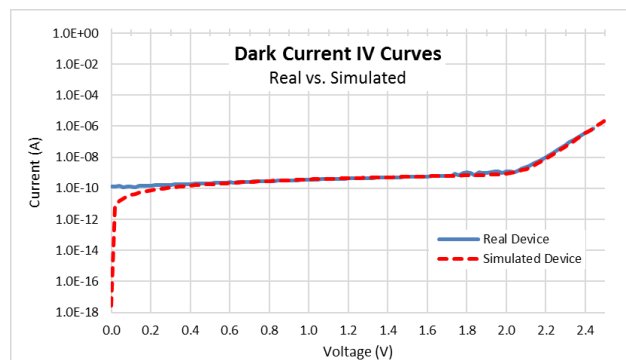


Figure 5 GaN device dark current IV curves, real vs. simulated [9]

The nonlinear response of the device power efficiency and MPP (and eventual reduction of power output) with kinetic energy of the electron beam is indicative of the limited depth of the device energy conversion. The nonlinear response can be divided into 2 distinct regions of power generation (Fig. 7). The first occurs during lower energy electron stimulation (<11.25 keV). The electrons deposit all their energy in the volume of the device where charge collection can occur (depletion region). The second regime is for electron energies (>11.25 keV), where EHP creation takes place beyond the depletion region. Higher energy electrons increase the energy deposited, but less of it is available to be collected and converted into electrical current output. The 2 distinct regions of power generation as a function of input electron energy emphasize the fact that when the energy deposition range exceeds that of the depletion region, the device is no longer as efficient at collecting the charge generated in EHP creation.

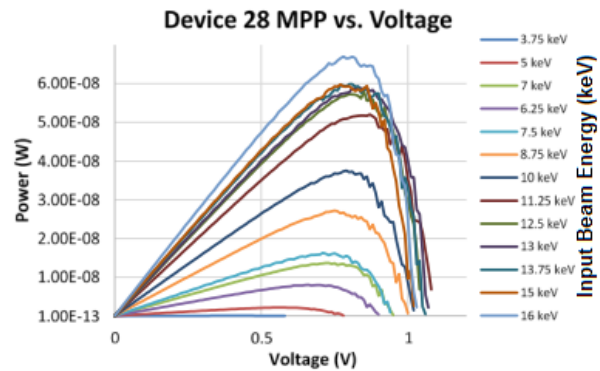


Figure 6 GaN device power generation vs forward bias, showing MPP for each applied beam energy [2]

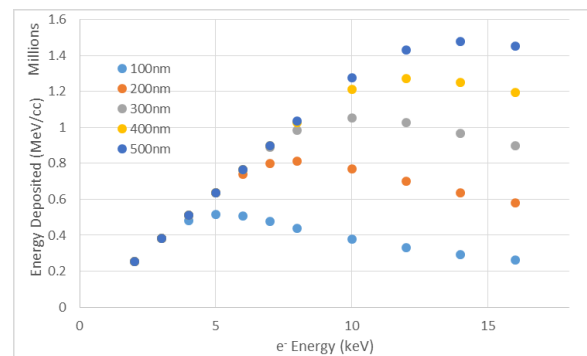


Figure 7 GaN energy deposition efficiency for GaN device depth ranging from 100 nm to 500 nm [9]

Device simulations, MCNPX and Silvaco, show the similar change in slope of the MPP. As fabrication of GaN with less defects is not yet possible, to optimize a GaN device for betavoltaic operation means matching the depletion region to the energy deposition resulting from radiation. Improving short circuit current can be achieved through extending the depletion region volume to the energy deposition profile. Improving the MPP can be achieved by having the p-n junction placed where the most energy deposition occurs in the device. The difference between the model and measured device I-V currents is suspected to be according to the metal contact of the device blocking the input electron beam. The impact of the metal contact effectively shields the semiconductor, reducing the effective EHP generation within the depletion region. This is shown especially at the lower keV electron energies.

The first phase of the investigation of material parameters was through a direct comparison to the measured device dark current. Through software simulation and dark current characterization it was found that the depletion region formed by the internal electric field was found to be 500 nm in width. A variety of material parameters were investigated that affect the operation of a betavoltaic energy converter, providing insight into limitations in GaN growth techniques for future device fabrication. The minority carrier lifetime is the parameter that affects operation the most, directly

driving diffusion collection. SRH recombination is, thus, the most important parameter to identify for valid simulation. Radiative and surface recombination were found to have negligible effect, and will continue to be negligible until the SRH recombination improves. The tunneling effective mass was shown to greatly change the electron beam stimulated current result; however, the default value of $0.25 m_0$ provides the optimum fit to data. The shunt resistance for a device is a macroscopic parameter that includes both material properties and surface effects. The modeling parameter R_{sh} ($2.7 \text{ G}\Omega$) that best matched the measured result was identified during the dark current verification phase of this research and was used for all following simulations.

The best device efficiency was achieved when the electron range was matched to the depletion region. The model result defining the depletion region on the order of 500 nm, which corresponds to the 6-keV electron range, correlates well with the change in slope of the MPP. The matching of the I-V curves is the best comparison of simulation to experiment. The input electron beam current in the model differs from the measured device experiment, especially at the lower keV electron energies, which can be explained by the metal contact layer on the p-type GaN shields the lower energy electrons. This produces a larger discrepancy between the model and measured input electron beam current below 10 keV. The next iteration will be to include the effect of the metal contact through changing the EHP generation profile, producing a new set of modeled I-V curves.

Conclusion

The trends generated in the models compare well with measured data and serve to verify the material properties and operation of the GaN energy conversion process. This successful verification now permits the model to be GaN devices with differing initial beta energy spectrums for simulations of various beta energy sources, and different initial GaN geometric designs. The simulations to date describe monenergetic electron beams directed towards the GaN device that directly compared to a first set of experimental measured results. The next application of this verified result will be to use a broad beta spectrum that will provide efficiency results (energy conversion) of this device when using the isotopes of ^3H and ^{63}Ni . Energy deposition as a function of depth within GaN will be numerically calculated from the beta spectra for ^3H and ^{63}Ni , and applied to calculate the performance and efficiency of the GaN device under isotope exposure. These beta spectra will allow investigation into the optimization of GaN betavoltaic device structure. 3-D structures that increase the surface area on a wafer footprint will be investigated. Both etched mesa structures and 3D P-u-N pillared GaN structures on a wafer will be investigated for increasing efficiency on a wafer.

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